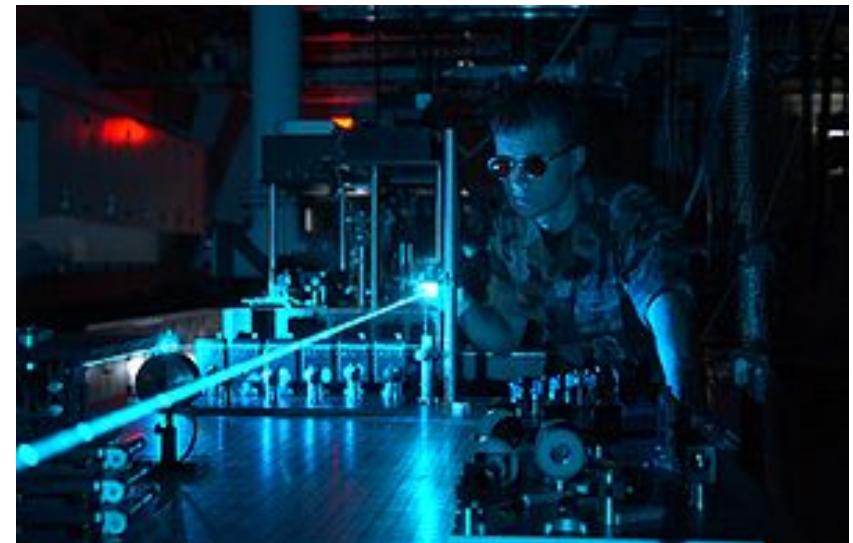
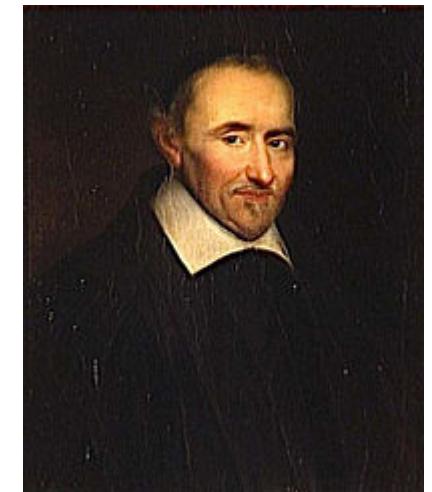


# Nature of Light



# Nature of Light: particles?

Crookes radiometer (erroneous explanation in terms of particles)



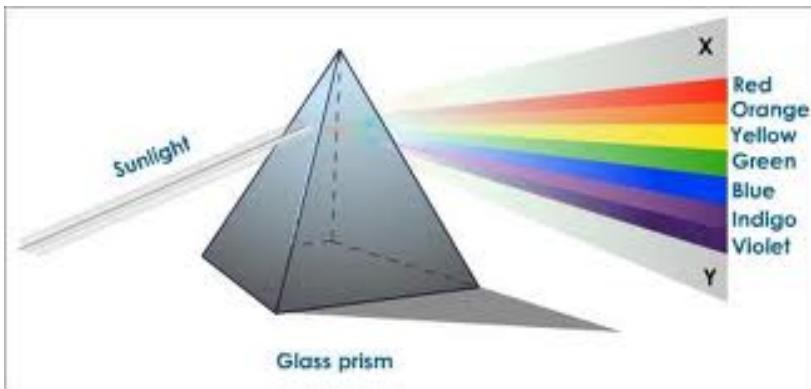
Pierre Gassendi



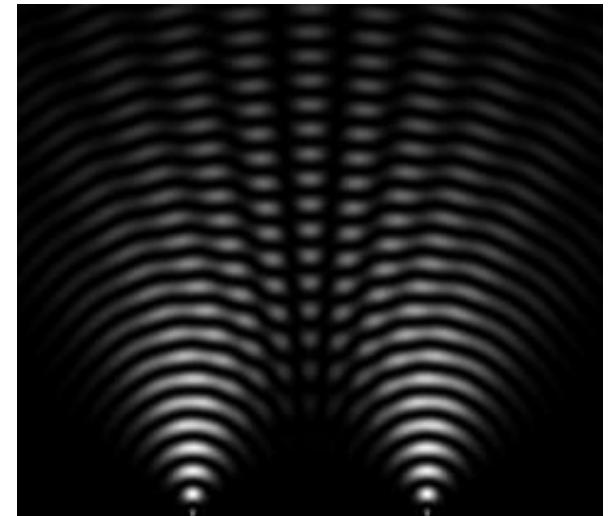
Isaac Newton  
(*Hypothesis of Light, Opticks*)

# Nature of Light: waves?

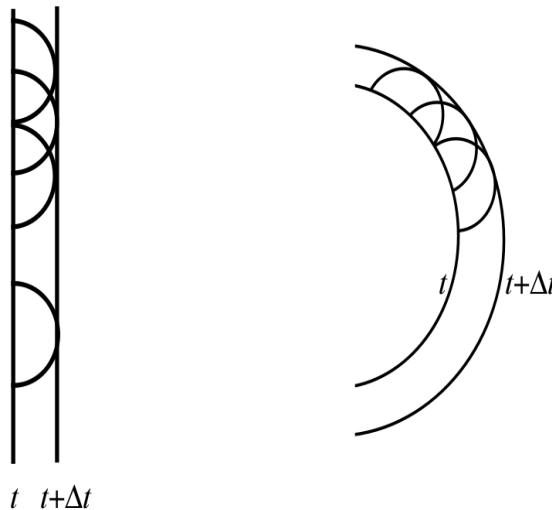
*dispersion*



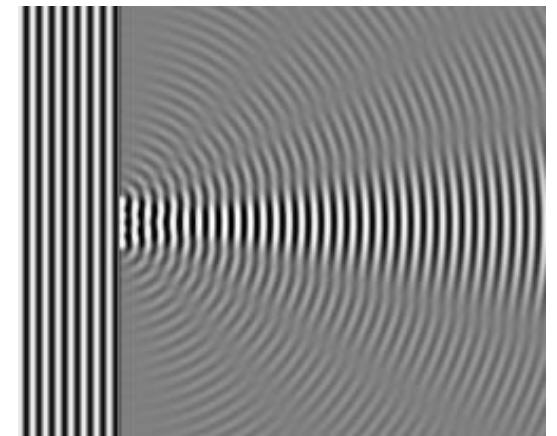
*interference*



*Huygens principle*



*diffraction*

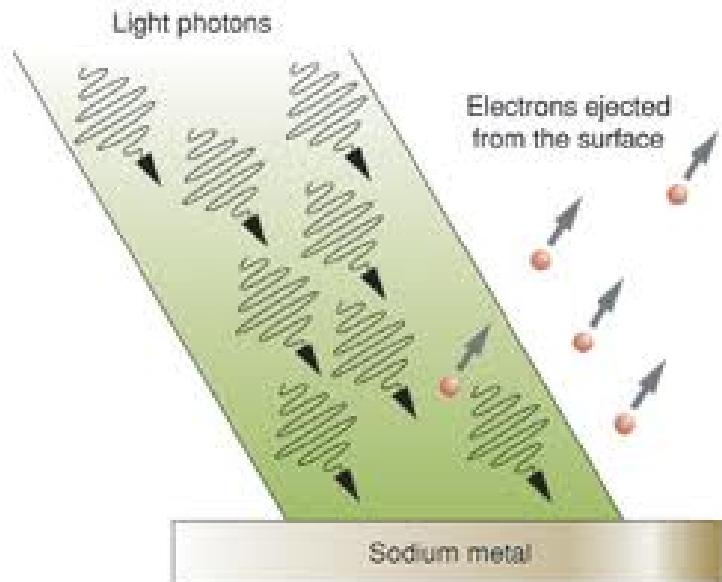


Augustin-Jean Fresnel, Robert Hooke,  
Simeon Denis Poisson, Christian Huygens

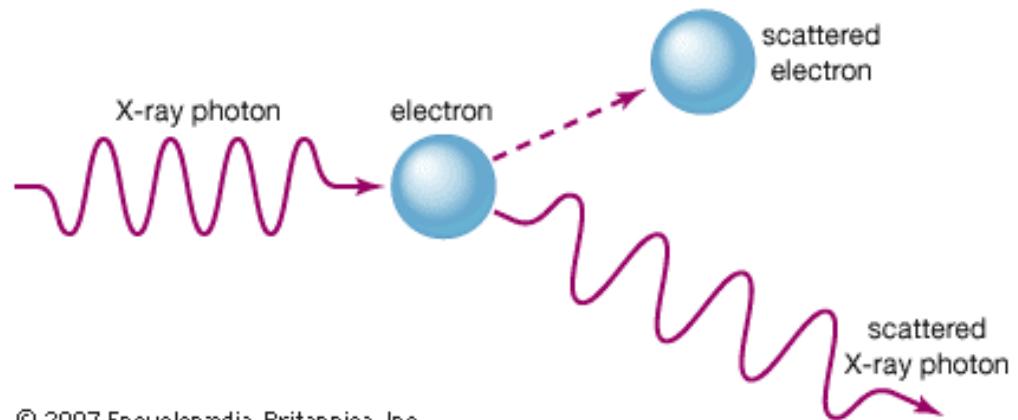
Images: Wikimedia Commons

# Quantitative Approach: particles...

Image: Wikimedia Commons



photoelectric effect



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Compton effect

Albert Einstein, Arthur Holly Compton

# ...or electromagnetic waves?

Propagation of an Electromagnetic Wave

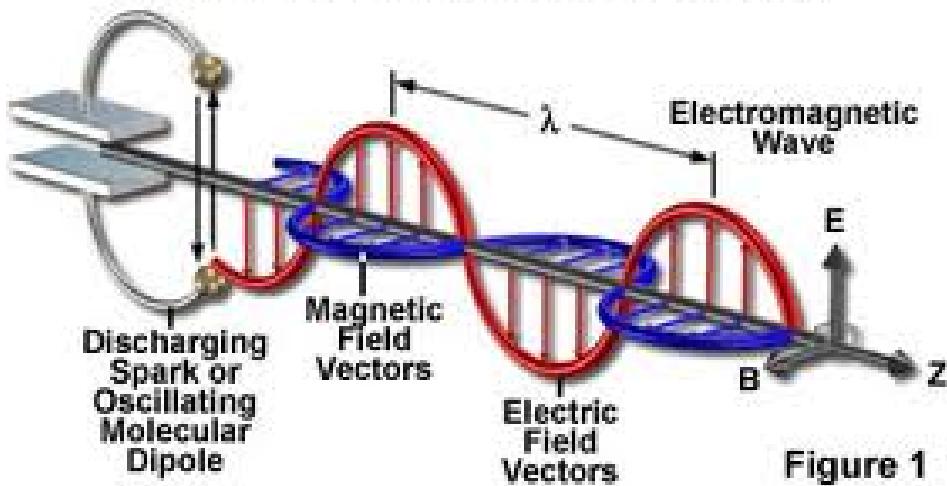
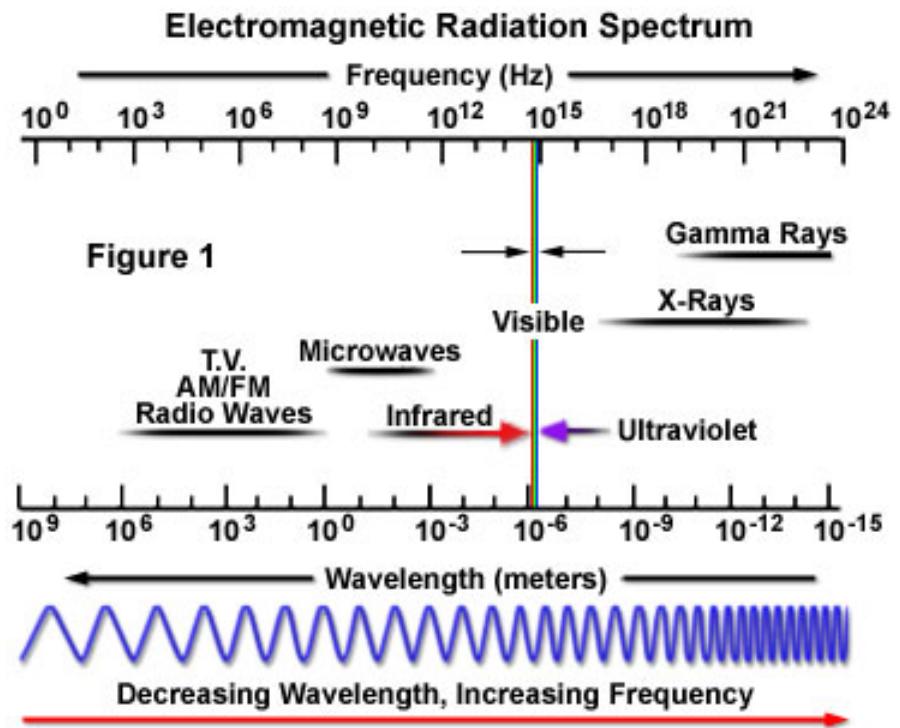
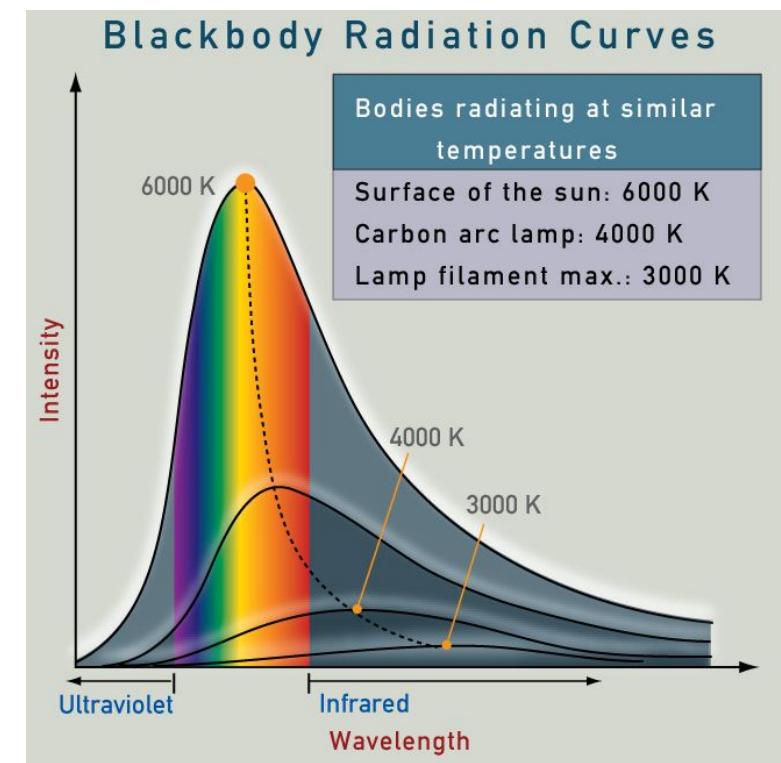
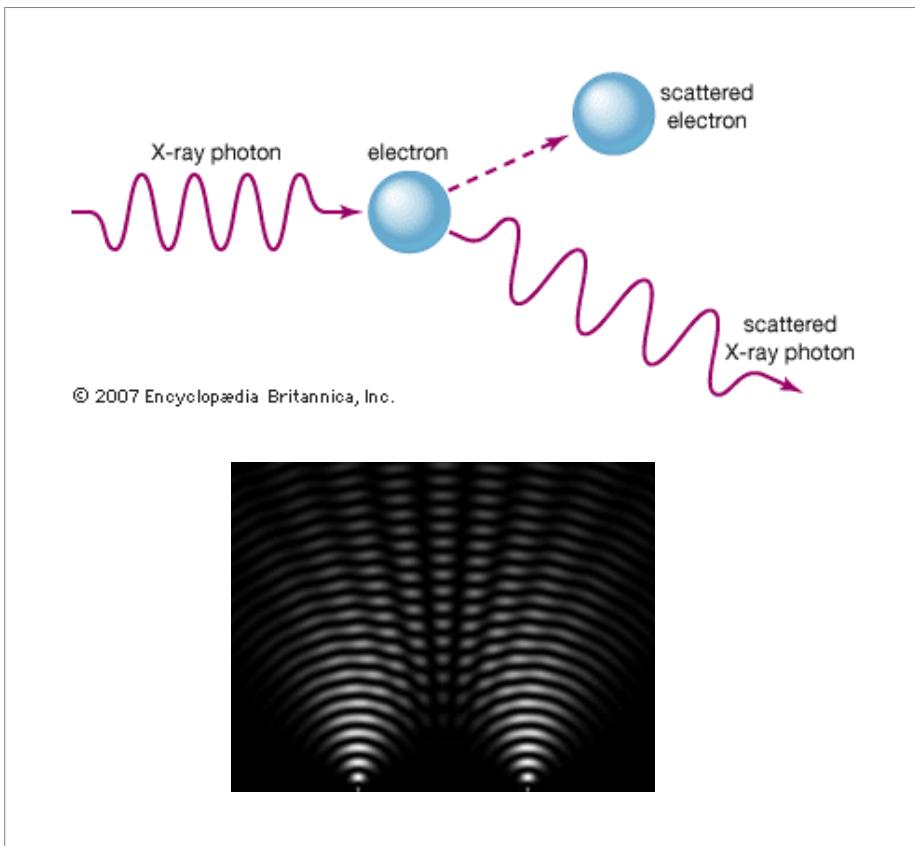


Figure 1



# Answer: dual nature (particles & waves)



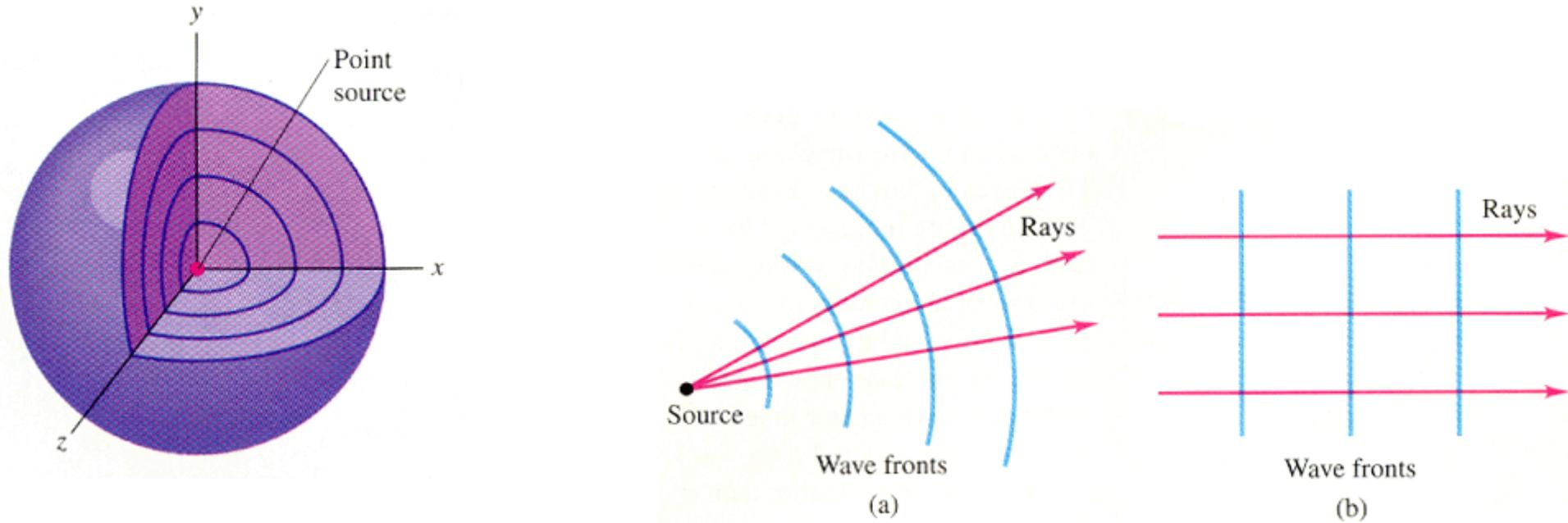
Max Planck, Davisson and Germer, Louis de Broglie

Quantum Electrodynamics (QED)

Richard Feynman, Freeman Dyson, Julian Schwinger, Shin-Itiro Tomonaga

# Vocabulary

**Wave front –** set of points (in 3D – a surface) having the same phase

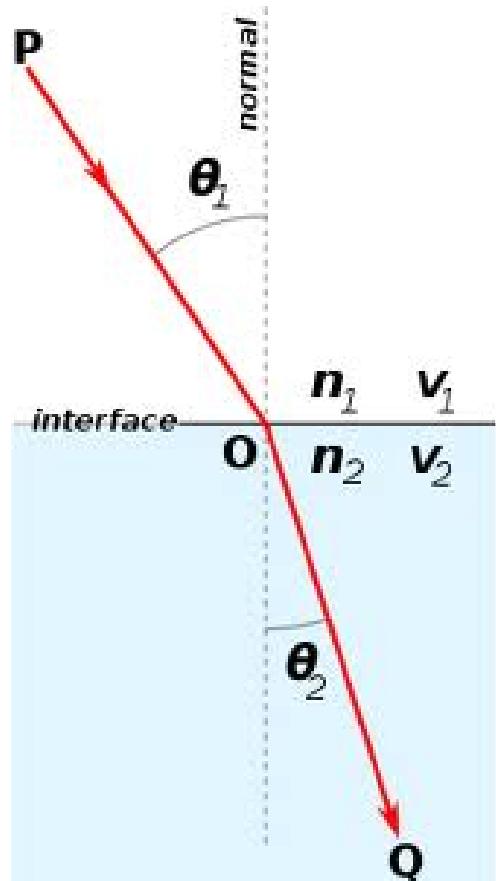


**Ray –** line along the direction of propagation of the wave

In isotropic and homogeneous materials rays are straight lines perpendicular to wave fronts

# Reflection and Refraction

**Fermat's principle:** *Light follows the path of least travel time.*

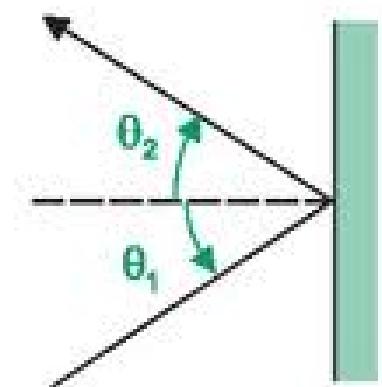


**Law of refraction (Snell's law)**

$$\frac{\sin \theta_1}{\sin \theta_2} = \frac{n_2}{n_1} \quad n_i = \frac{c}{v_i}$$

**Law of reflection**

$$\theta_1 = \theta_2$$



**NB.** All rays and the line normal to the boundary lie in the same plane.

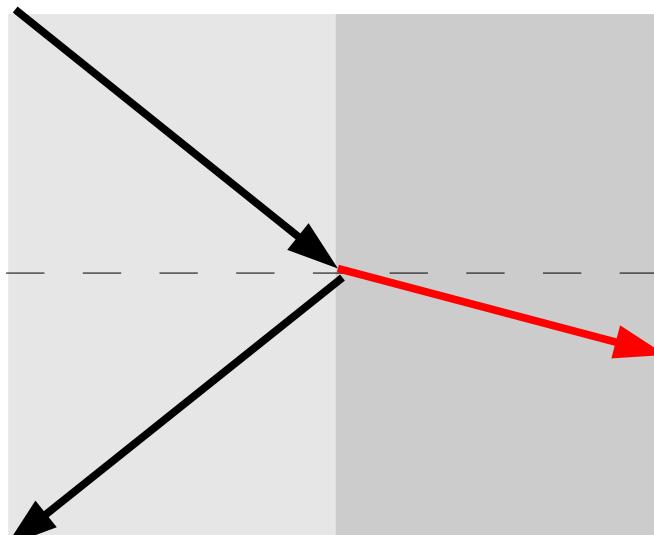
# Discussion

Snell's law

$$\frac{\sin \theta_1}{\sin \theta_2} = \frac{n_2}{n_1}$$

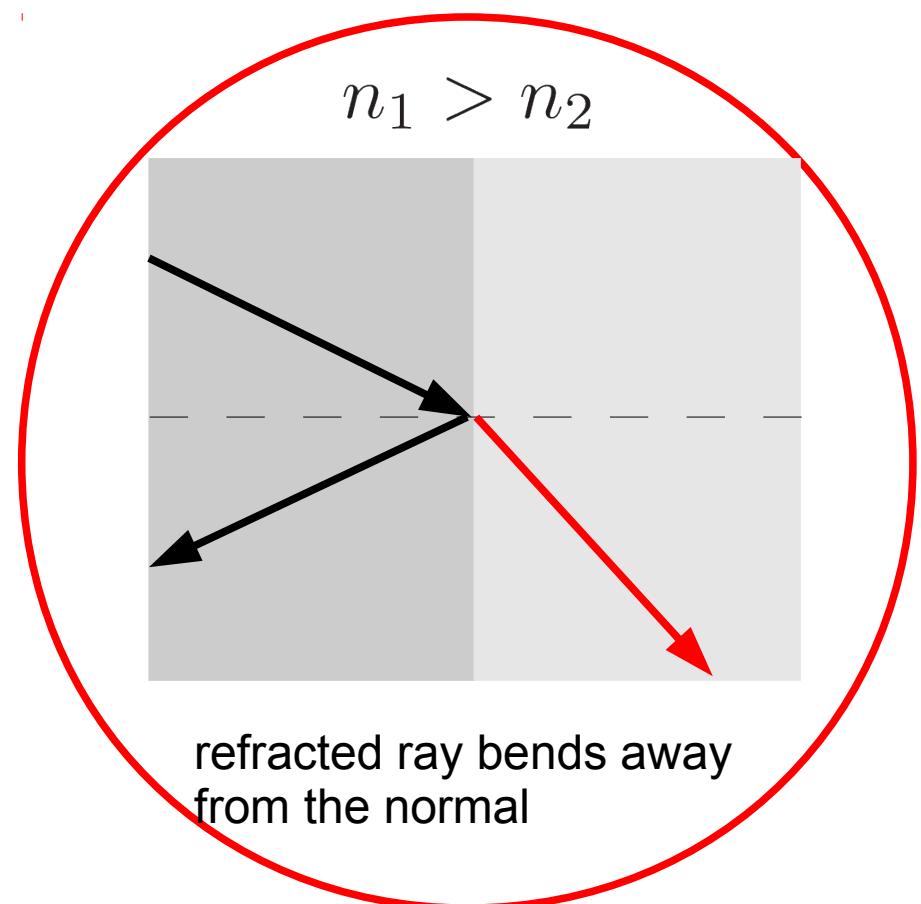
$$n_i = \frac{c}{v_i}$$

$$n_1 < n_2$$



refracted ray bends toward  
the normal

$$n_1 > n_2$$



refracted ray bends away  
from the normal

**NB.** For normal incidence, all angles are zero.

# Index of Refraction (also called Refractive Index)

Table 18 INDEX OF REFRACTION

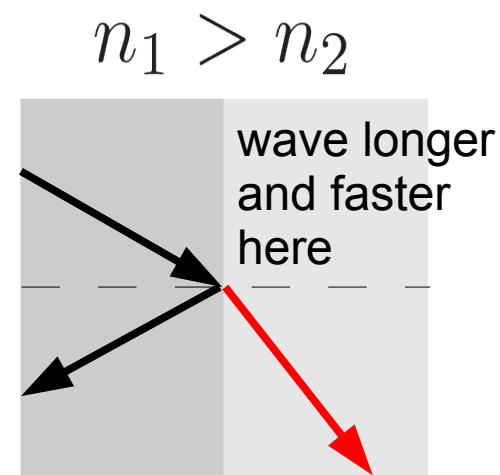
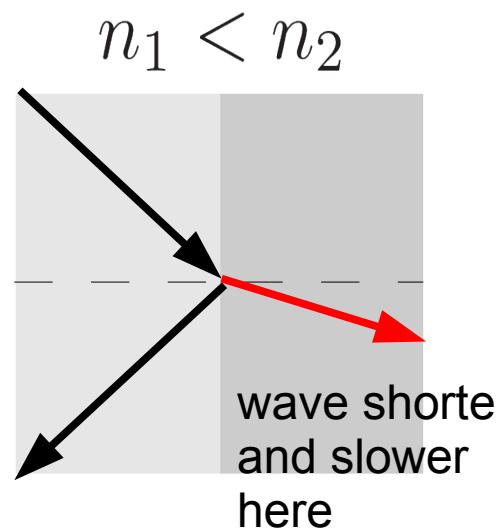
( $\lambda = 5893 \text{ \AA}$ ; Temperature = 20 °C except as noted)

Material	Refractive index
air, dry (STP)	1.00029
alcohol, ethyl	1.360
benzene	1.501
calcite	1.6583
	1.4864
canada balsam	1.530
carbon dioxide (STP)	1.00045
carbon disulfide	1.625
carbon tetrachloride	1.459
diamond	2.4195
glass, crown	1.5172
flint	1.6270
glycerol	1.475
ice	1.310
lucite	1.50
quartz	1.544
	1.553
quartz, fused	1.45845
sapphire ( $\text{Al}_2\text{O}_3$ )	1.7686
	1.7604
water, distilled	1.333
water vapor (STP)	1.00025

# Index of Refraction

- (1) The frequency  $f$  of the wave does not change when passing from one material to another.  $v = \lambda f$
- (2) The wavelength  $\lambda$  is different in different materials.

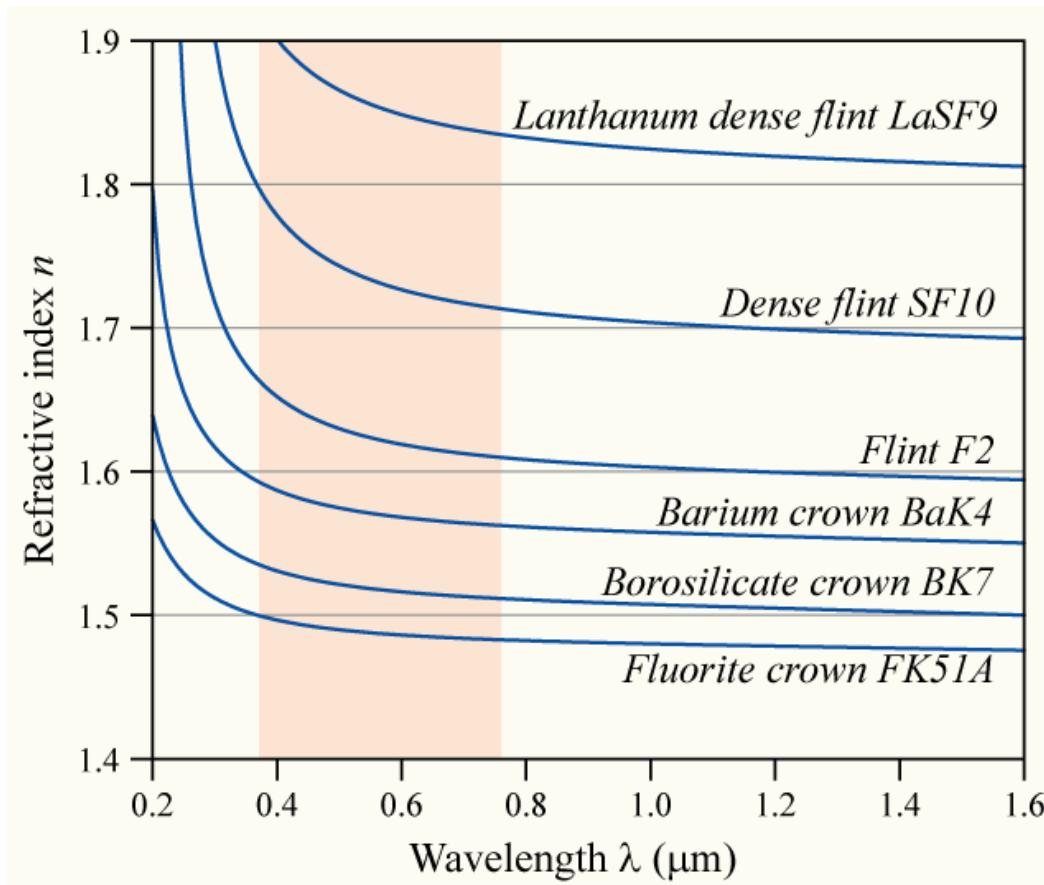
$$\frac{c}{\lambda_0} = \frac{v}{\lambda} \Rightarrow \lambda = \frac{\lambda_0}{n}$$



In general, the index of refraction depends on the wavelength – **dispersion**.

# Dispersion

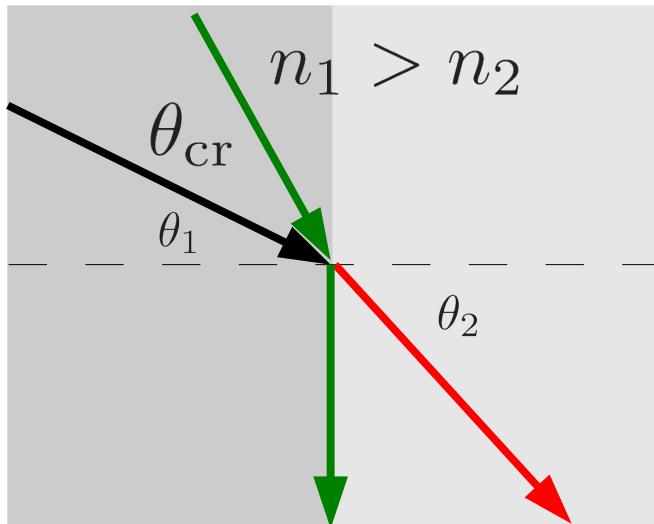
In most materials,  $n$  decreases with increasing wavelength.



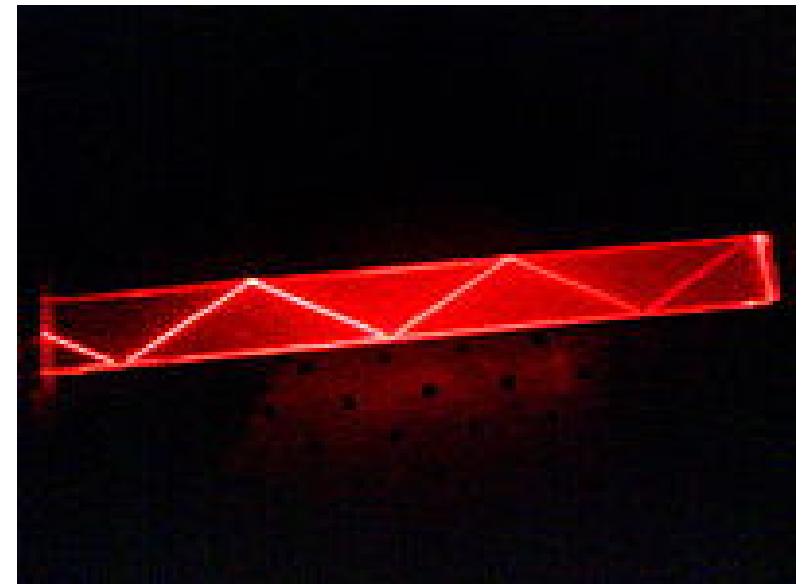
can be modelled by driven harmonic oscillators

# Discussion: Total Internal Reflection

Consider light incident upon a medium of smaller index of refraction.



applications: fiber optics



$$\text{Snell's law} \quad \frac{\sin \theta_1}{\sin \theta_2} = \frac{n_2}{n_1}$$

total internal reflection for  
 $\theta_1 \geq \theta_{\text{cr}}$

$$\sin \theta_{\text{cr}} = \frac{n_2}{n_1}$$

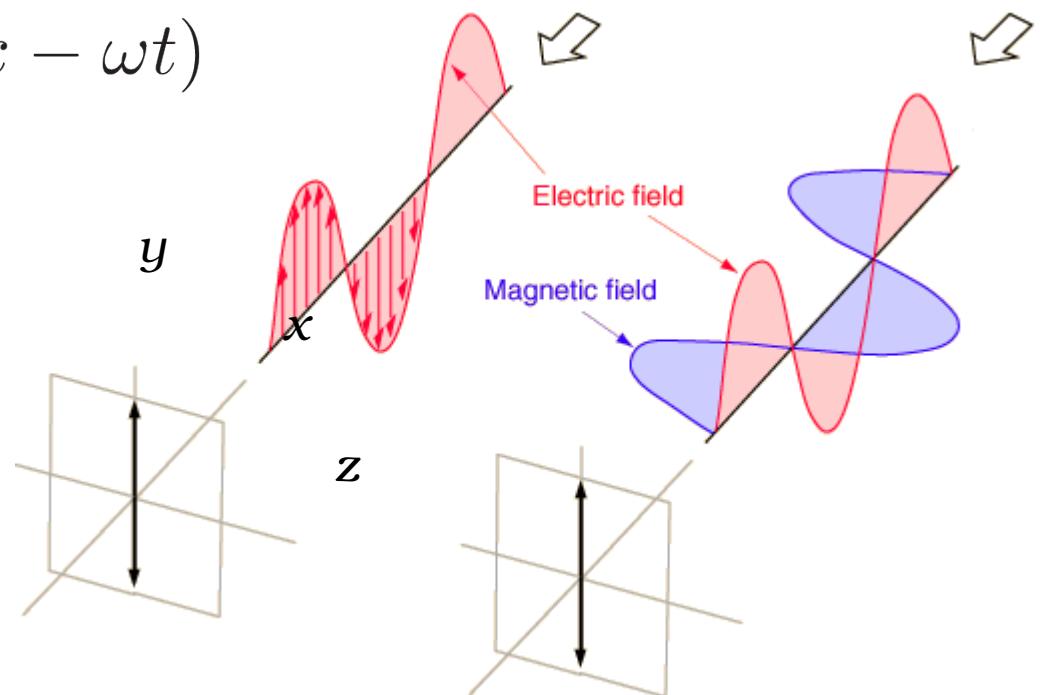
# Polarization of Light: Linear Polarization

Recall that, polarization of the electromagnetic wave is determined by the direction of the **electric field** vector.

$$\mathbf{E}(\mathbf{r}, t) = E_0 \hat{n}_y \cos(kx - \omega t)$$

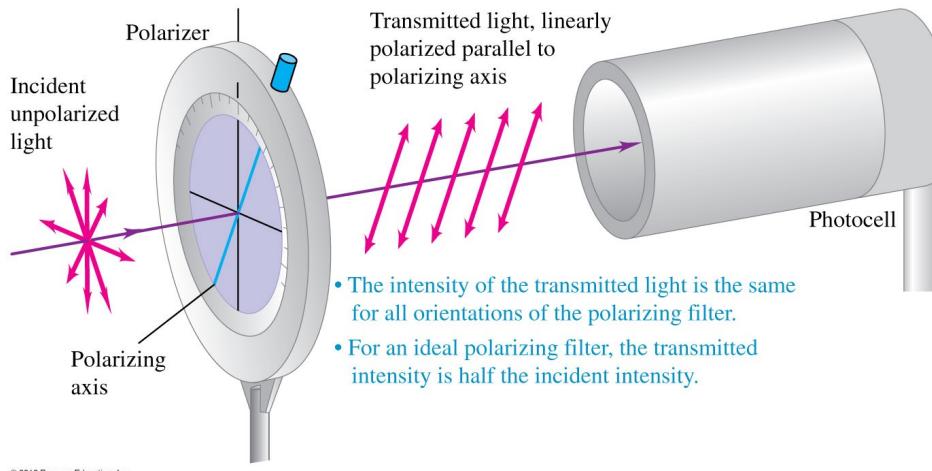
$$\mathbf{B}(\mathbf{r}, t) = -B_0 \hat{n}_z \cos(kx - \omega t)$$

e-m wave polarized  
in the  $y$  direction



# Polarization and Malus' Law

single polarizer

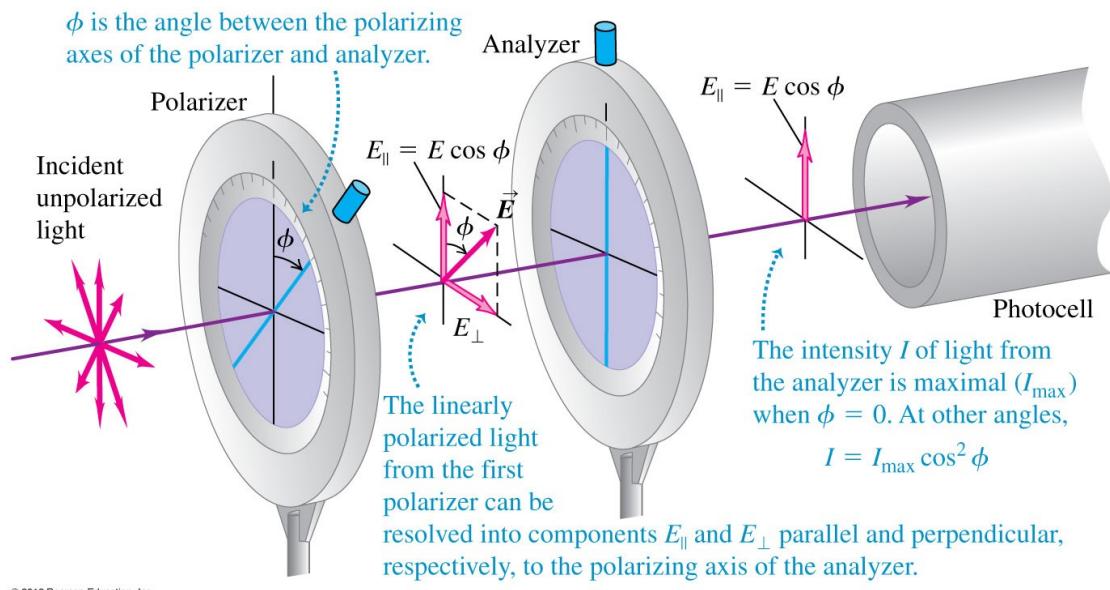


polarizer + analyzer

Malus' law

$$I = I_0 \cos^2 \phi$$

NB.  $I_0$  is the intensity of the linearly polarized light incident on the analyzer



# Polarizers and Malus' Law

## Unpolarized (Natural) Light

### Polarization of Light Waves

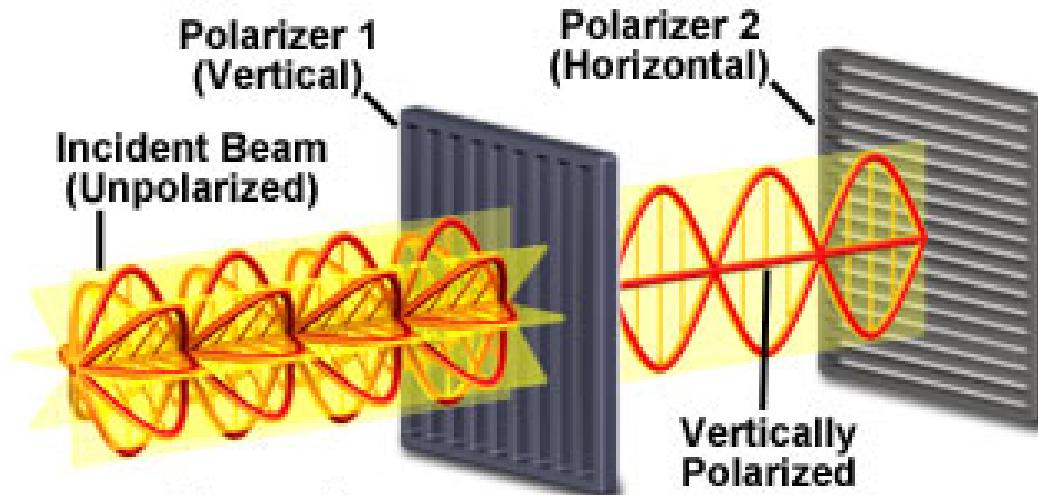


Figure 1

$$I_{\text{polarized}} = \frac{1}{2} I_{\text{unpolarized}}$$

linear polarization

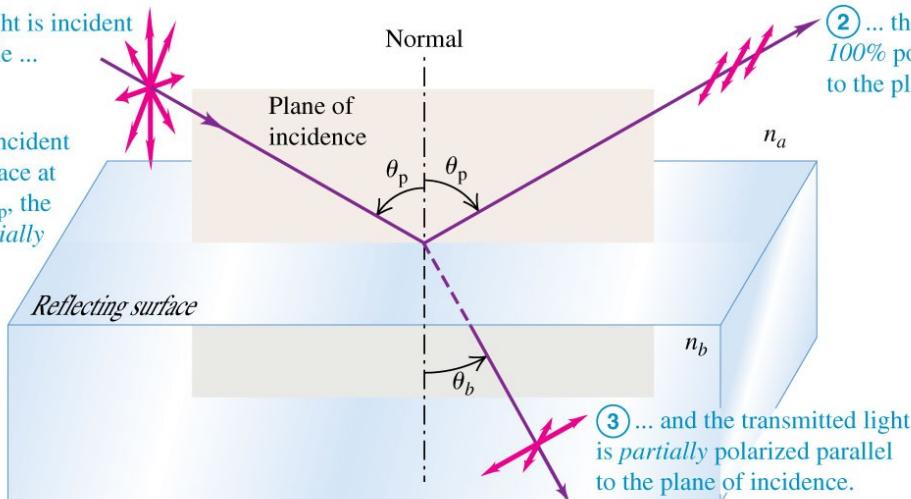
unpolarized light = statistical mixture of waves polarized in all possible, equally-probable, directions

$$I_{\text{pol}} = \lim_{N \rightarrow \infty} \left( \frac{I_{\text{unp}}}{N} \cos^2 \phi_1 + \frac{I_{\text{unp}}}{N} \cos^2 \phi_2 + \cdots + \frac{I_{\text{unp}}}{N} \cos^2 \phi_N \right)$$

$$I_{\text{pol}} = I_{\text{unp}} \lim_{N \rightarrow \infty} \frac{1}{N} \sum_{i=1}^N \cos^2 \phi_i = I_{\text{unp}} \langle \cos^2 \phi \rangle = \frac{I_{\text{unp}}}{2}$$

# Polarization by Reflection

① If unpolarized light is incident at the polarizing angle ...



④ Alternatively, if unpolarized light is incident on the reflecting surface at an angle other than  $\theta_p$ , the reflected light is *partially* polarized.

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② ... then the reflected light is 100% polarized perpendicular to the plane of incidence ...

③ ... and the transmitted light is partially polarized parallel to the plane of incidence.

$$\text{Snell's law} \quad \frac{\sin \theta_p}{\sin \theta_b} = \frac{n_b}{n_a}$$

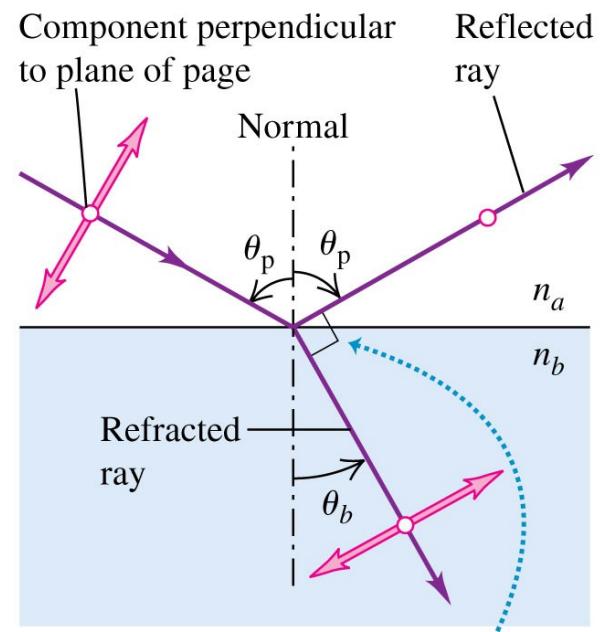
for light incident at polarizing angle

$$\theta_b + \theta_p = \frac{\pi}{2}$$

Brewster's law

$$\theta_p = \arctan \frac{n_b}{n_a}$$

Note: This is a side view of the situation shown in Fig. 33.27.

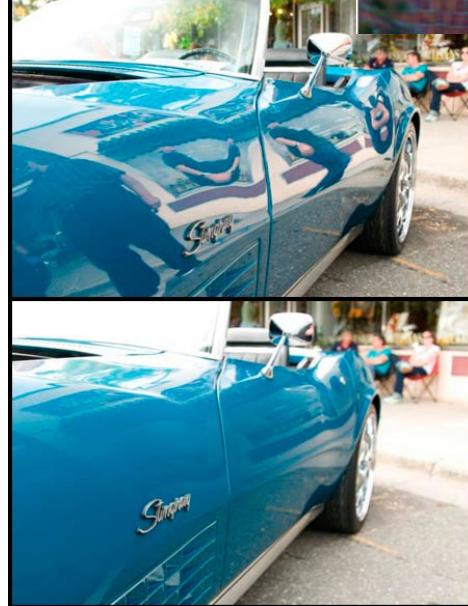


When light strikes a surface at the polarizing angle, the reflected and refracted rays are perpendicular to each other and

$$\tan \theta_p = \frac{n_b}{n_a}$$

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# Applications in Photography



eliminates reflexes

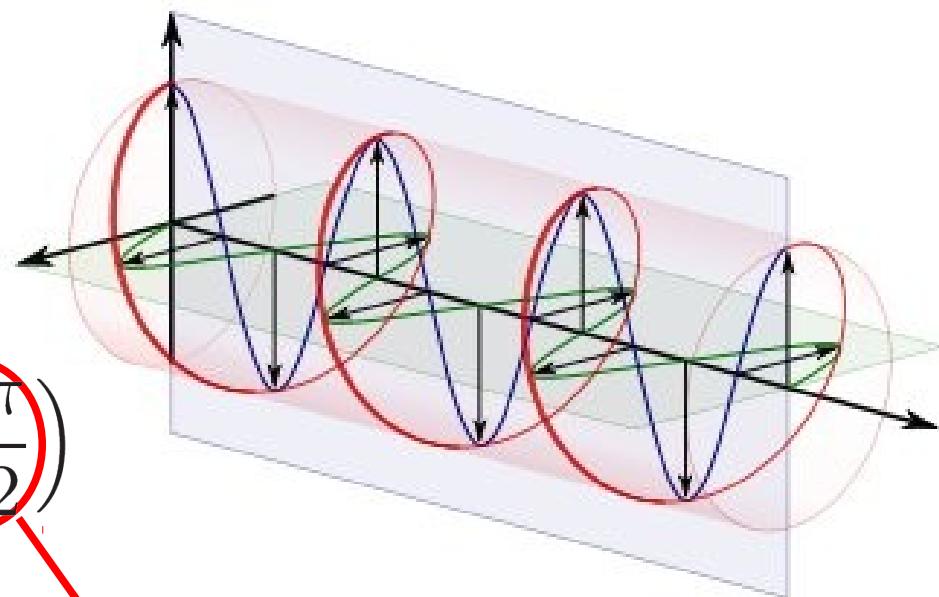


# Circular Polarization

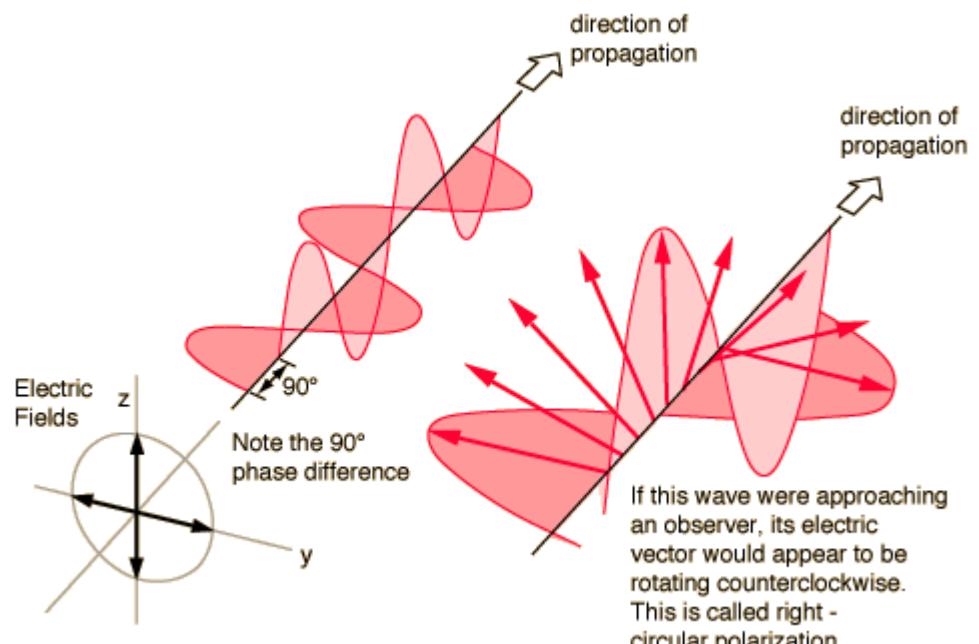
Superposition of two e-m waves

$$\mathbf{E}_1(\mathbf{r}, t) = E_0 \hat{n}_y \cos(kx - \omega t)$$

$$\mathbf{E}_2(\mathbf{r}, t) = E_0 \hat{n}_z \cos\left(kx - \omega t - \frac{\pi}{2}\right)$$



phase difference  
(quarter of a cycle)

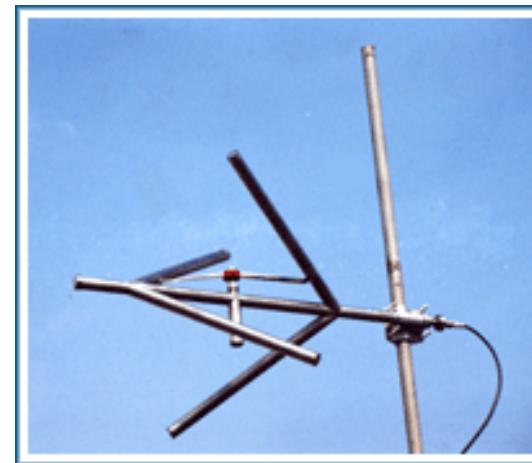


# Circular Polarization

Practical implementations of quarter-cycle phase shift.

## radio frequencies

Use two perpendicular antennas with a phase-shifting module.



## light

Use a *birefringent* crystal (e.g. calcite or quartz); refractive index different for different polarizations of incident light.

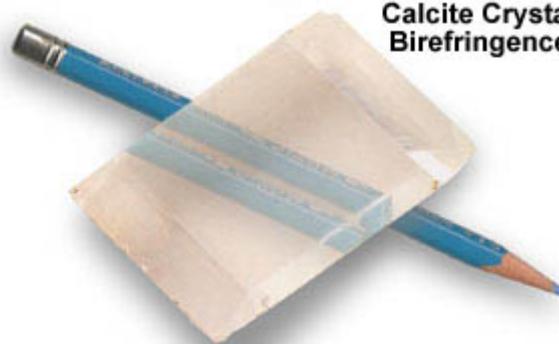
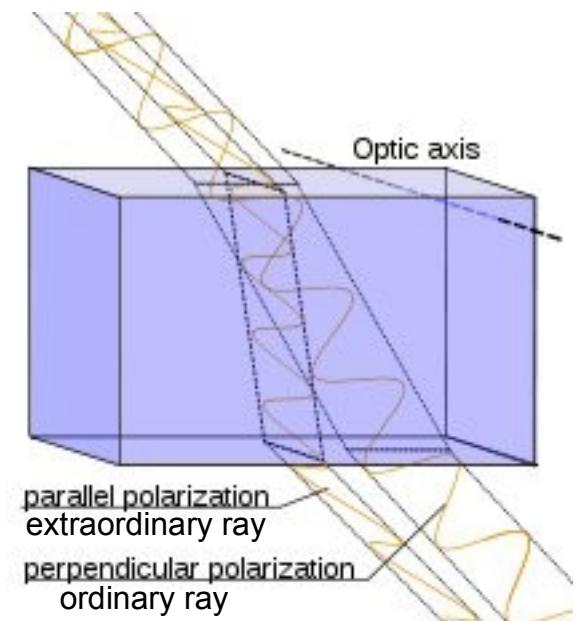
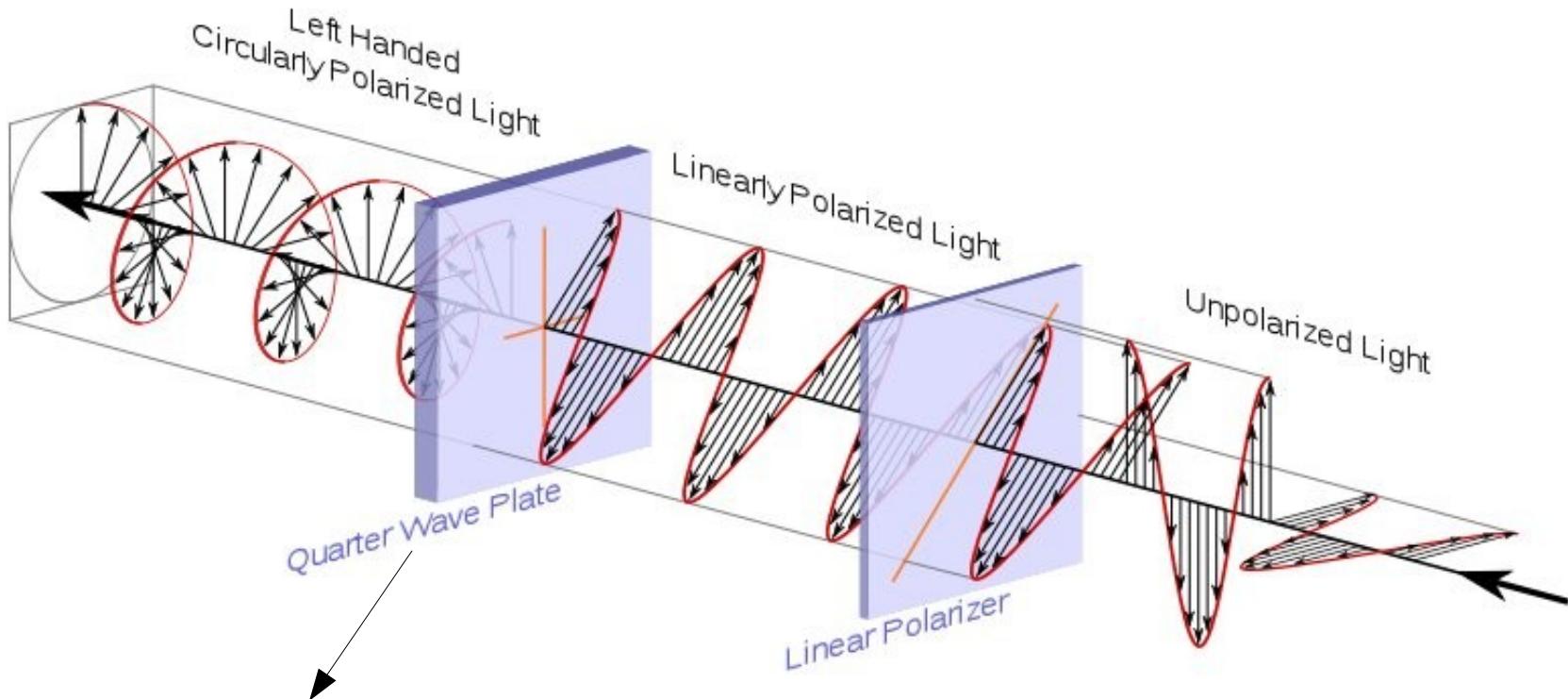


Figure 2



phases differ!

# Circular Polarization

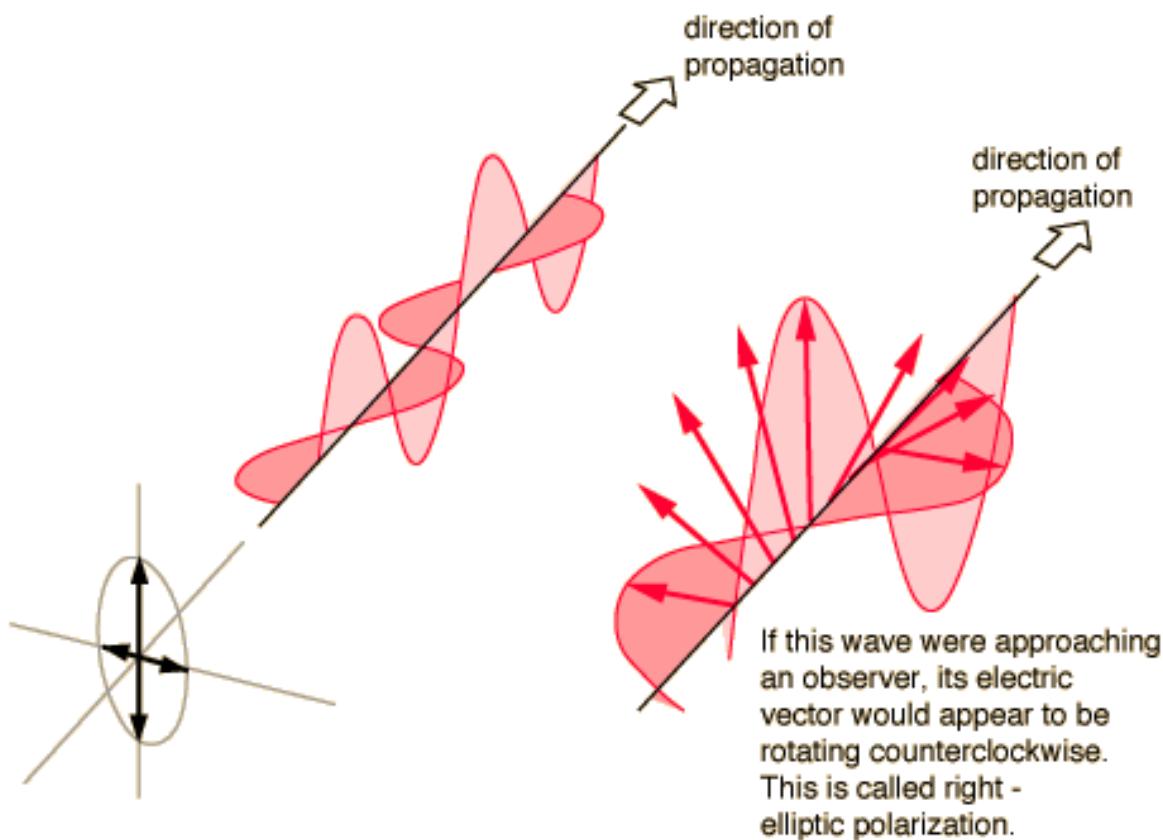


birefringent crystal with a thickness  
corresponding to the quarter-cycle phase shift

\* Theoretical description of birefringence: consider dielectric permittivity as a 2<sup>nd</sup> order tensor (matrix) rather than a scalar (consequently, the refractive index also has a tensor structure).

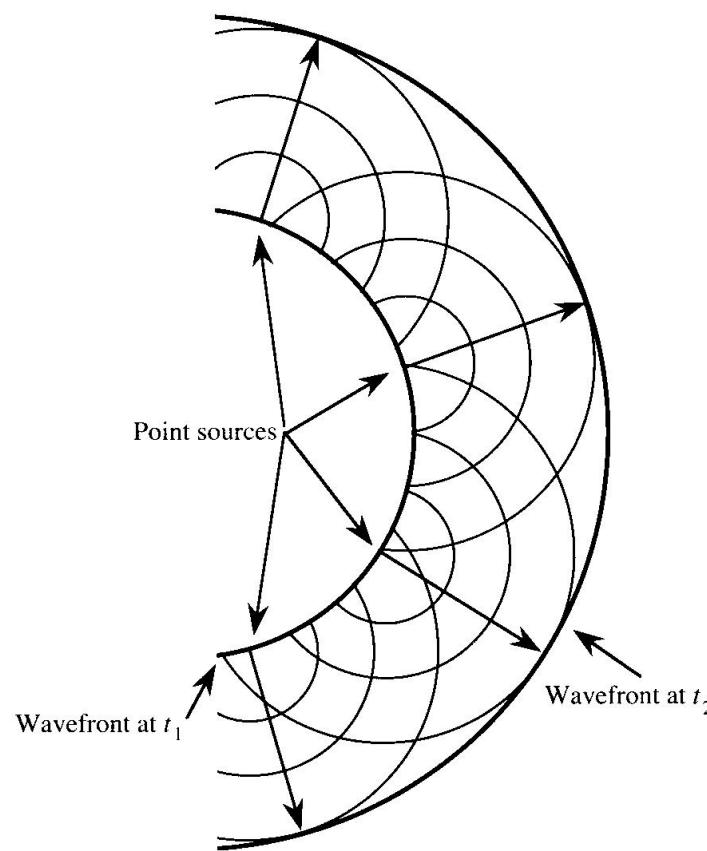
# Elliptical Polarization

Elliptically polarized light is a superposition of two e-m waves of *unequal* amplitude, linearly polarized in perpendicular directions, differing in phase by 90°.



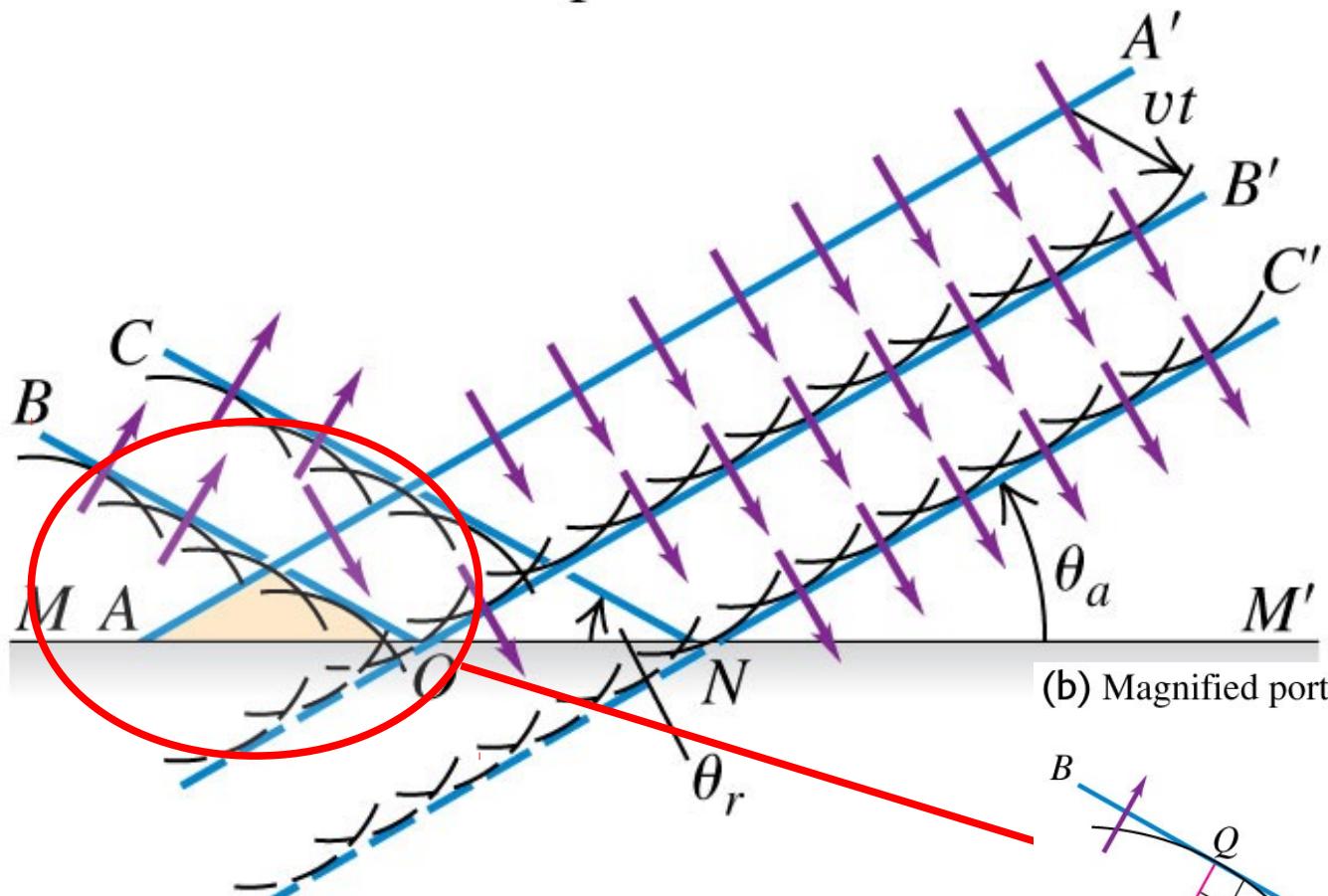
# Huygens' (or Huygens-Fresnel) Principle

*Every point of the wavefront may be considered as a source of secondary wavelets that propagate out in all directions with speed equal to speed of propagation of the wave.*

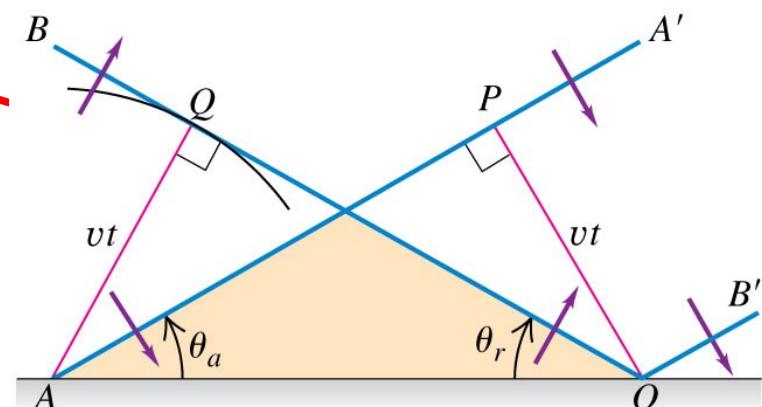


# Huygens' principle: Reflection

(a) Successive positions of a plane wave  $AA'$  as it is reflected from a plane surface

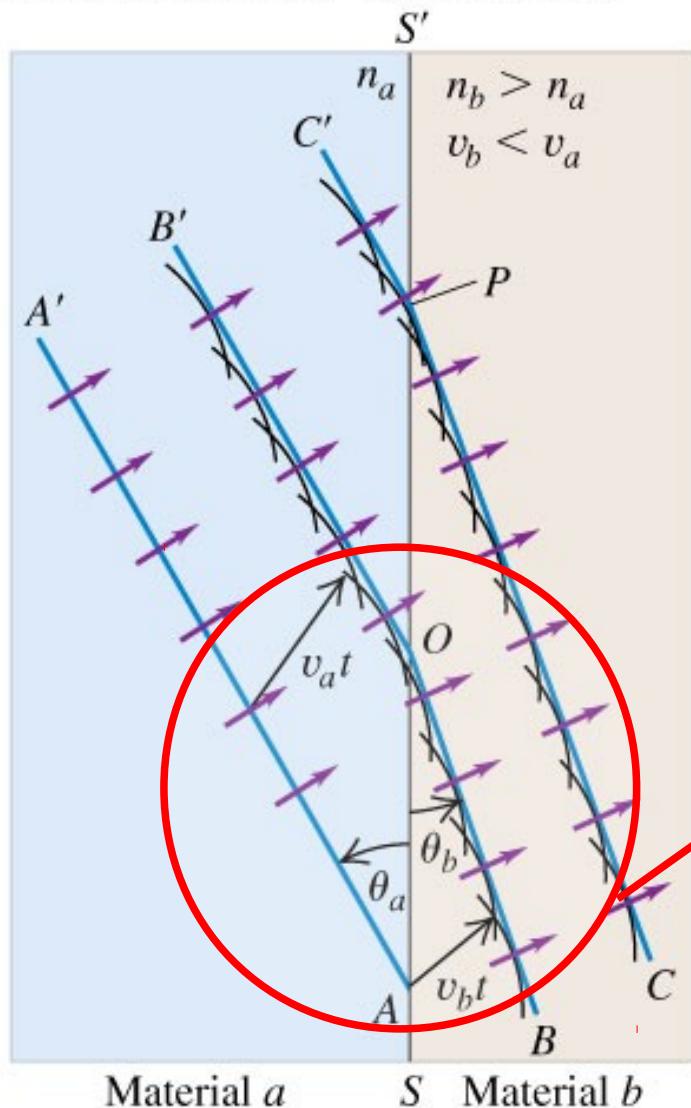


(b) Magnified portion of (a)



# Huygens' Principle: Refraction

(a) Successive positions of a plane wave  $AA'$  as it is refracted by a plane surface



(b) Magnified portion of (a)

